## Appendix E

# Characteristics and Earthquake Performance of RVS Building Types

## E.1 Introduction

For the purpose of the RVS, building structural framing types have been categorized into fifteen types listed in Section 3.7.1 and shown in Table 3-1. This appendix provides additional information about each of these structural types, including detailed descriptions of their characteristics, common types of earthquake damage, and common seismic rehabilitation techniques.

## E.2 Wood Frame (W1, W2)

### *E.2.1 Characteristics*

Wood frame structures are usually detached residential dwellings, small apartments, commercial buildings or one-story industrial structures. They are rarely more than three stories tall, although older buildings may be as high as six stories, in rare instances. (See Figures E-1 and E-2)

Figure E-1 Single family residence (an example of the W1 identifier, light wood-frame residential and commercial buildings less than 5000 square feet).

Wood stud walls are typically constructed of 2-inch by 4-inch wood members vertically set about 16 inches apart. (See Figures E-3 and E-4). These walls are braced by plywood or equivalent material, or by diagonals made of wood or steel. Many detached single family and low-rise multiple family residences in the United States are of stud wall wood frame construction.

Figure E-2 Larger wood-framed structure, typically with room-width spans (W2, light, wood-frame buildings greater than 5000 square feet).

Post and beam construction, which consists of larger rectangular (6 inch by 6 inch and larger) or sometimes round wood columns framed together with large wood beams or trusses, is not common and is found mostly in older buildings. These buildings usually are not residential, but are larger buildings such as warehouses, churches and theaters.

Timber pole buildings (Figures E-5 and E-6) are a less common form of construction found mostly in suburban and rural areas. Generally adequate seismically when first built, they are more often subject to wood deterioration due to the exposure of the columns, particularly near the ground surface. Together with an often-found "soft story" in this building type, this deterioration may contribute to unsatisfactory seismic performance.

In the western United States, it can be assumed that all single detached residential houses (i.e., houses with rear and sides separate from adjacent structures) are wood stud frame structures unless visual or supplemental information indicates otherwise (in the Southwestern U.S., for example, some residential homes are constructed of adobe, rammed earth, and other non-wood materials). Many houses that appear to have brick exterior facades are actually wood frame with nonstructural brick veneer or brick-patterned synthetic siding.

In the central and eastern United States, brick walls are usually not veneer. For these houses the

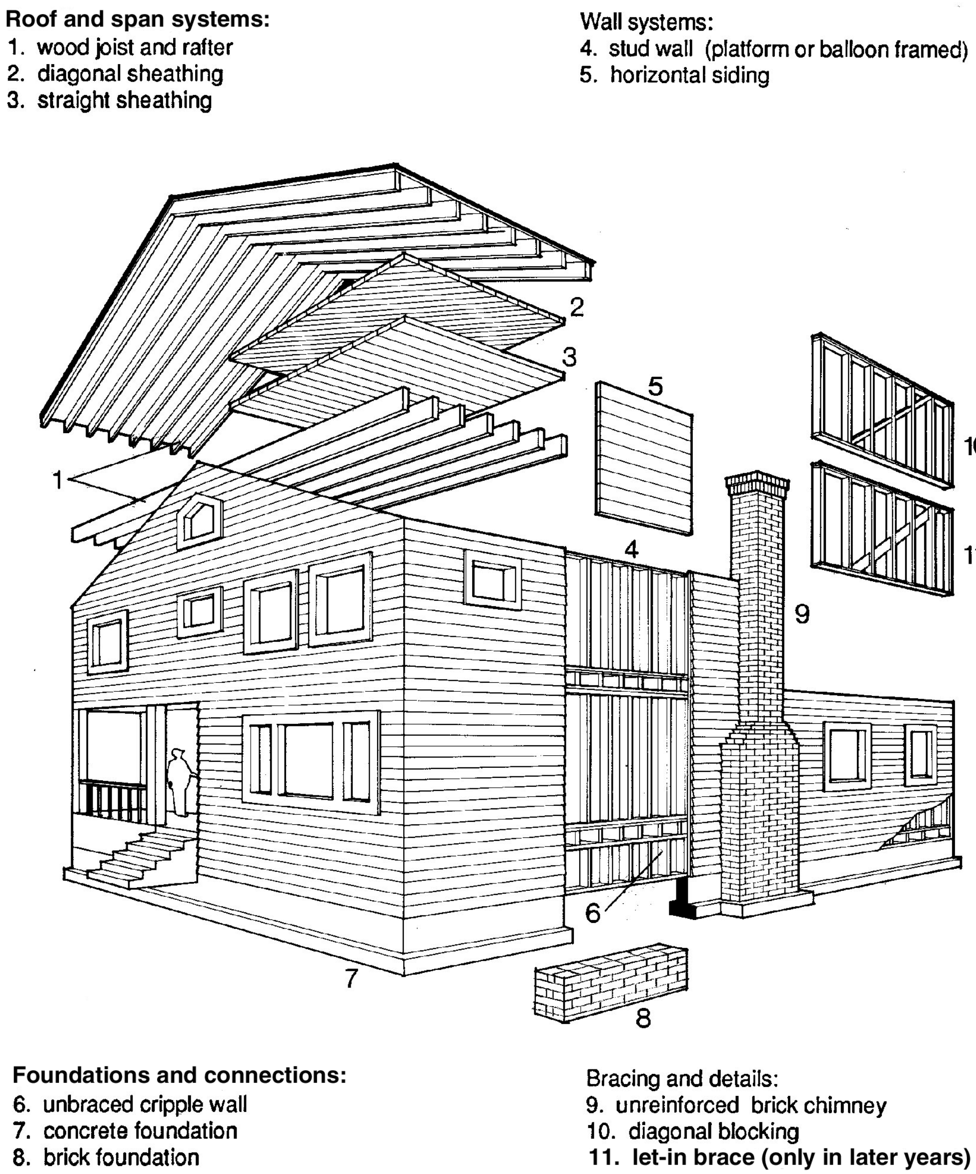


Figure E-3 Drawing of wood stud frame construction.

brick-work must be examined closely to verify that it is real brick. Second, the thickness of the exterior wall is estimated by looking at a window or door opening. If the wall is more than 9 inches from the interior finish to exterior surface, then it may be a brick wall. Third, if header bricks exist in the brick pattern, then it may be a brick wall. If these features all point to a brick wall, the house can be assumed to be a masonry building, and not a wood frame.

In wetter, humid climates it is common to find homes raised four feet or more above the outside grade with this space totally exposed (no foundation walls). This allows air flow under the house, to minimize decay and rot problems associated with high humidity and enclosed spaces. These houses are supported on wood post and small precast concrete pads or piers. A common name for this construction is post and pier construction.

### *E.2.2 Typical Earthquake Damage*

Stud wall buildings have performed well in past earthquakes due to inherent qualities of the structural system and because they are lightweight and low-rise. Cracks in any plaster or stucco may appear, but these seldom degrade the strength of the building and are classified as nonstructural damage. In fact, this

Figure E-4 Stud wall, wood-framed house.

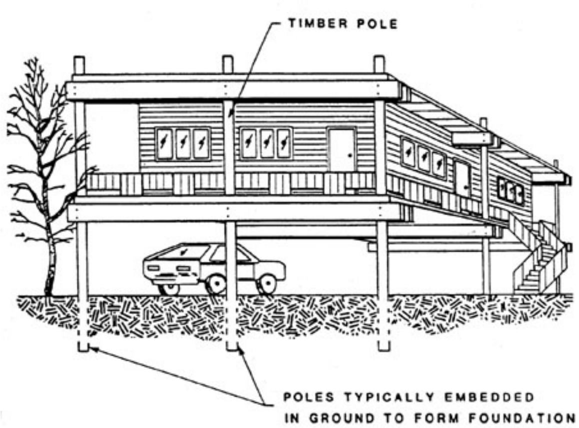


Figure E-5 Drawing of timber pole framed house.

Figure E-6 Timber pole framed house.

type of damage helps dissipate the earthquake-induced energy of the shaking house. The most common type of structural damage in older buildings results from a lack of adequate connection between the house and the foundation. Houses can slide off their foundations if they are not properly bolted to the foundations. This movement (see Figure E-7) results in major damage to the building as well as to plumbing and electrical connections. Overturning of

Figure E-7 House off its foundation, 1983 Coalinga earthquake.

the entire structure is usually not a problem because of the low-rise geometry. In many municipalities, modern codes require wood structures to be adequately bolted to their foundations. However, the year that this practice was adopted will differ from community to community and should be checked.

Many of the older wood stud frame buildings have no foundations or have weak foundations of unreinforced masonry or poorly reinforced concrete. These foundations have poor shear resistance to horizontal seismic forces and can fail.

Another problem in older buildings is the stability of cripple walls. Cripple walls are short stud walls between the foundation and the first floor level. Often these have no bracing neither in-plane nor out-of-plane and thus may collapse when subjected to horizontal earthquake loading. If the cripple walls collapse, the house will sustain considerable damage and may collapse. In some older homes, plywood sheathing nailed to the cripple studs may have been used to rehabilitate the cripple walls. However, if the sheathing is not nailed adequately to the studs and

Figure E-8 Failed cripple stud wall, 1992 Big Bear earthquake.

foundation sill plate, the cripple walls will still collapse (see Figure E-8).

Homes with post and pier perimeter foundations, which are constructed to provide adequate air flow under the structure to minimize the potential for decay, have little resistance to earthquake forces. When these buildings are subjected to strong earthquake ground motions, the posts may rotate or slip of the piers and the home will settle to the ground. As with collapsed cripple walls, this can be very expensive damage to repair and will result in the home building “red-tagged” per the ATC-20 post-earthquake safety evaluation procedures (ATC, 1989, 1995). See Figure E-9.

Figure E-9 Failure of post and pier foundation, Humboldt County.

Garages often have a large door opening in the front wall with little or no bracing in the remainder of the wall. This wall has almost no resistance to lateral forces, which is a problem if a heavy load such as a second story is built on top of the garage. Homes built over garages have sustained damage in past earthquakes, with many collapses. Therefore the house-over-garage configuration, which is found commonly in low-rise apartment complexes and some newer suburban detached dwellings, should be examined more carefully and perhaps rehabilitated.

Unreinforced masonry chimneys present a life-safety problem. They are often inadequately tied to the house, and therefore fall when strongly shaken. On the other hand, chimneys of reinforced masonry generally perform well.

Some wood-frame structures, especially older buildings in the eastern United States, have masonry veneers that may represent another hazard. The veneer usually consists of one wythe of brick (a wythe is a term denoting the width of one brick) attached to the stud wall. In older buildings, the veneer is either insufficiently attached or has poor quality mortar, which often results in peeling of the veneer during moderate and large earthquakes.

Post and beam buildings (not buildings with post and pier foundations) tend to perform well in earthquakes, if adequately braced. However, walls often do not have sufficient bracing to resist horizontal motion and thus they may deform excessively.

### *E.2.3 Common Rehabilitation Techniques*

In recent years, especially as a result of the Northridge earthquake, emphasis has been placed on addressing the common problems associated with light-wood framing. This work has concentrated mainly in the western United States with single-family residences.

The rehabilitation techniques focus on houses with continuous perimeter foundations and cripple walls. The rehabilitation work consists of bolting the house to the foundation and providing plywood or other wood sheathing materials to the cripple walls to strengthen them (see Figure E-10). This is the most cost-effective rehabilitation work that can be done on a single-family residence.

Little work has been done in rehabilitating timber pole buildings or post and pier construction. In timber pole buildings rehabilitation techniques are focused on providing resistance to lateral forces by bracing (applying sheathing) to interior walls, creating a continuous load path to the ground. For homes with post and pier perimeter foundations, the work has focused on providing partial foundations and bracing to carry the earthquake loads.

Figure E-10 Seismic strengthening of a cripple wall, with plywood sheathing.

## E.3 Steel Frames (S1, S2)

### *E.3.1 Characteristics*

Steel frame buildings generally may be classified as either moment-resisting frames or braced frames, based on their lateral-force-resisting systems. Moment-resisting frames resist lateral loads and deformations by the bending stiffness of the beams and columns (there is no diagonal bracing). In concentric braced frames the diagonal braces are connected, at each end, to the joints where beams and columns meet. The lateral forces or loads are resisted by the tensile and compressive strength of the bracing. In eccentric braced frames, the bracing is slightly offset from the main beam-to-column connections, and the short section of beam is expected to deform significantly in bending under major seismic forces, thereby dissipating a considerable portion of the energy of the vibrating building. Each type of steel frame is discussed below.

***Moment-Resisting Steel Frame***

Typical steel moment-resisting frame structures usually have similar bay widths in both the transverse and longitudinal direction, around 20-30 ft (Figure E-11). The load-bearing frame consists of beams and columns distributed throughout the building. The floor diaphragms are usually concrete,

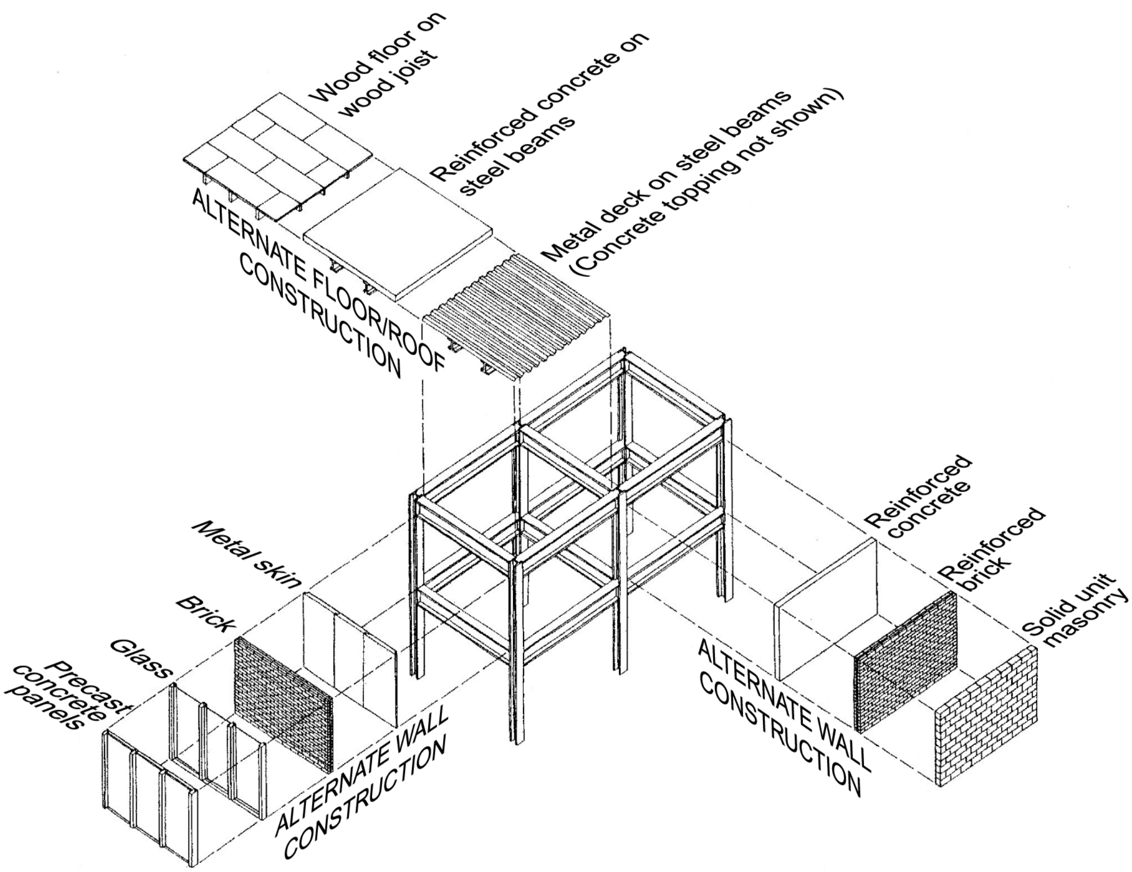


Figure E-11 Drawing of steel moment-resisting frame building.

sometimes over steel decking. Moment-resisting frame structures built since 1950 often incorporate prefabricated panels hung onto the structural frame as the exterior finish. These panels may be precast concrete, stone or masonry veneer, metal, glass or plastic.

This structural type is used for commercial, institutional and other public buildings. It is seldom used for low-rise residential buildings.

Steel frame structures built before 1945 are usually clad or infilled with unreinforced masonry such as bricks, hollow clay tiles and terra cotta tiles and therefore should be classified as S5 structures (see Section E.6 for a detailed discussion). Other frame buildings of this period are encased in concrete. Wood or concrete floor diaphragms are common for these older buildings.

### *Braced Steel Frame*

Braced steel frame structures (Figures E-12 and E-13) have been built since the late 1800s with similar usage and exterior finish as the steel moment-frame buildings. Braced frames are sometimes used for long and narrow buildings because of their stiffness. Although these buildings are braced with diagonal members, the bracing members usually cannot be detected from the building exterior.

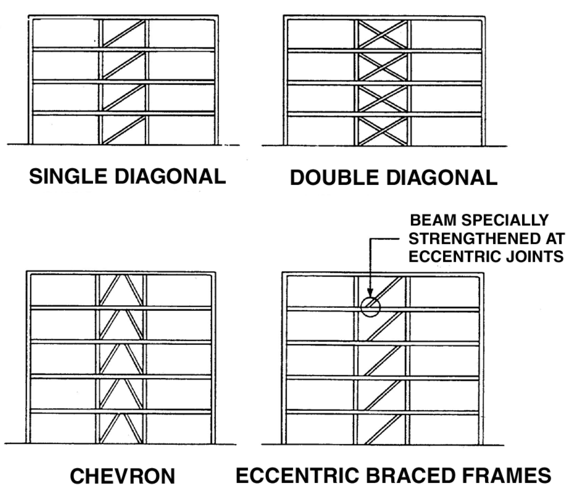


Figure E-12 Braced frame configurations.

From the building exterior, it is usually difficult to tell the difference between steel moment frames, braced frames, and frames with shear walls. In most modern buildings, the bracing or shear walls are located in the interior or covered by cladding material. Figure E-14 shows heavy diagonal bracing for a high rise building, located at the side walls, which

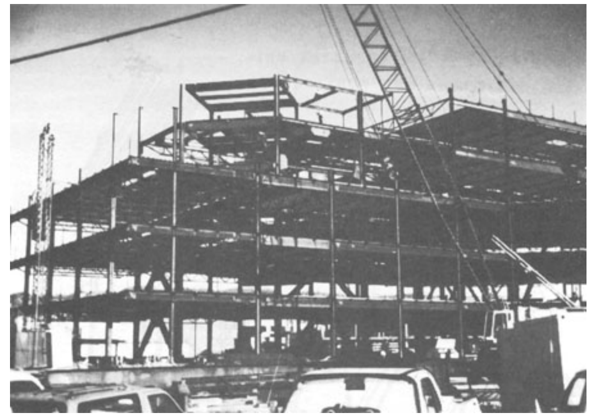

Figure E-13 Braced steel frame, with chevron and diagonal braces. The braces and steel frames are usually covered by finish material after the steel is erected.

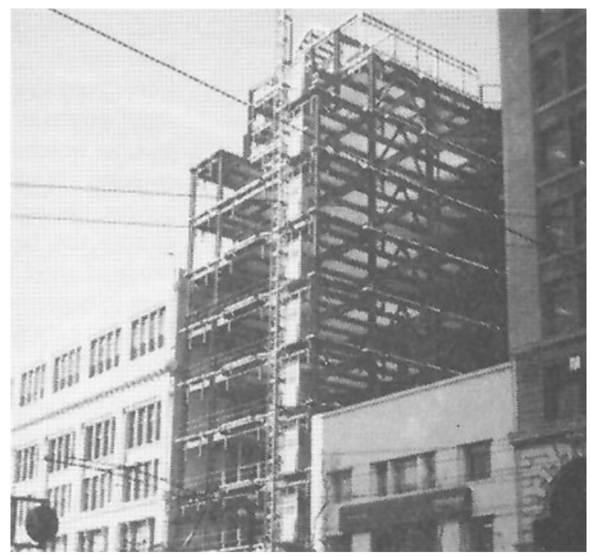

Figure E-14 Chevron bracing in steel building under construction.

will be subsequently covered by finish materials and will not be apparent. In fact, it is difficult to differentiate steel frame structures and concrete frame structures from the exterior. Most of the time, the structural members are clad in finish material. In older buildings, steel members can also be encased in concrete. There are no positive ways of distinguishing these various frame types except in the two cases listed below:

1. If a building can be determined to be a braced frame, it is probably a steel structure.

2. If exposed steel beams and columns can be seen, then the steel frame structure is apparent. (Especially in older structures, a structural frame which appears to be concrete may actually be a steel frame encased in concrete.)

### E.3.2 Typical Earthquake Damage

Steel frame buildings tend to be generally satisfactory in their earthquake resistance, because of their strength, flexibility and lightness. Collapse in earthquakes has been very rare, although steel frame buildings did collapse, for example, in the 1985 Mexico City earthquake. In the United States, these buildings have performed well, and probably will not collapse unless subjected to sufficiently severe ground shaking. The 1994 Northridge and 1995 Kobe earthquakes showed that steel frame buildings (in particular S1 moment-frame) were vulnerable to severe earthquake damage. Though none of the damaged buildings collapsed, they were rendered unsafe until repaired. The damage took the form of broken welded connections between the beams and columns. Cracks in the welds began inside the welds where the beam flanges were welded to the column flanges. These cracks, in some cases, broke the welds or propagated into the column flange, "tearing" the flange. The damage was found in those buildings that experienced ground accelerations of approximately 20% of gravity (20%g) or greater. Since 1994 Northridge, many cities that experienced large earthquakes in the recent past have instituted an inspection program to determine if any steel frames were damaged. Since steel frames are usually covered with a finish material, it is difficult to find damage to the joints. The process requires removal of the finishes and removal of fireproofing just to see the joint.

Possible damage includes the following.

1. Nonstructural damage resulting from excessive deflections in frame structures can occur to elements such as interior partitions, equipment, and exterior cladding. Damage to nonstructural elements was the reason for the discovery of damage to moment frames as a result of the 1994 Northridge earthquake.
2. Cladding and exterior finish material can fall if insufficiently or incorrectly connected.
3. Plastic deformation of structural members can cause permanent displacements.
4. Pounding with adjacent structures can occur.

### E.3.3 Common Rehabilitation Techniques

As a result of the 1994 Northridge earthquake many steel frame buildings, primarily steel moment frames, have been rehabilitated to address the problems discovered. The process is essentially to redo the connections, ensuring that cracks do not occur in the welds. There is careful inspection of the welding process and the electrodes during construction. Where possible, existing full penetration welds of the beams to the columns is changed so more fillet welding is used. This means that less heat is used in the welding process and consequently there is less potential for damage. Other methods include reducing welding to an absolute minimum by developing bolted connections or ensuring that the connection plates will yield (stretch permanently) before the welds will break. One other possibility for rehabilitating moment frames is to convert them to braced frames.

Figure E-15 Rehabilitation of a concrete parking structure using exterior X-braced steel frames.

The kind of damage discovered was not limited to moment frames, although they were the most affected. Some braced frames were found to have damage to the brace connections, especially at lower levels.

Structural types other than steel frames are sometimes rehabilitated using steel frames, as shown for the concrete structure in Figure E-15. Probably the most common use of steel frames for rehabilitation is in unreinforced masonry bearing-wall buildings (URM). Steel frames are typically used at the storefront windows as there is no available horizontal resistance provided by the windows in their plane. Frames can be used throughout the first floor perimeter when the floor area needs to be open, as in a restaurant. See Figure E-16.

When a building is encountered with this type of rehabilitation scheme, the building should be considered a frame type building S1 or S2.

## E.4 Light Metal (S3)

### *E.4.1 Characteristics*

Most light metal buildings existing today were built after 1950 (Figure E-17).They are used for agricultural structures, industrial factories, and warehouses. They are typically one story in height, sometimes without interior columns, and often enclose a large floor area. Construction is typically of steel frames spanning the short dimension of the building, resisting lateral forces as moment frames. Forces in the long direction are usually resisted by diagonal steel rod bracing. These buildings are usually clad with lightweight metal or asbestos-reinforced concrete siding, often corrugated.

To identify this construction type, the screener should look for the following characteristics:

Figure E-16 Use of a braced frame to rehabilitate an unreinforced masonry building.

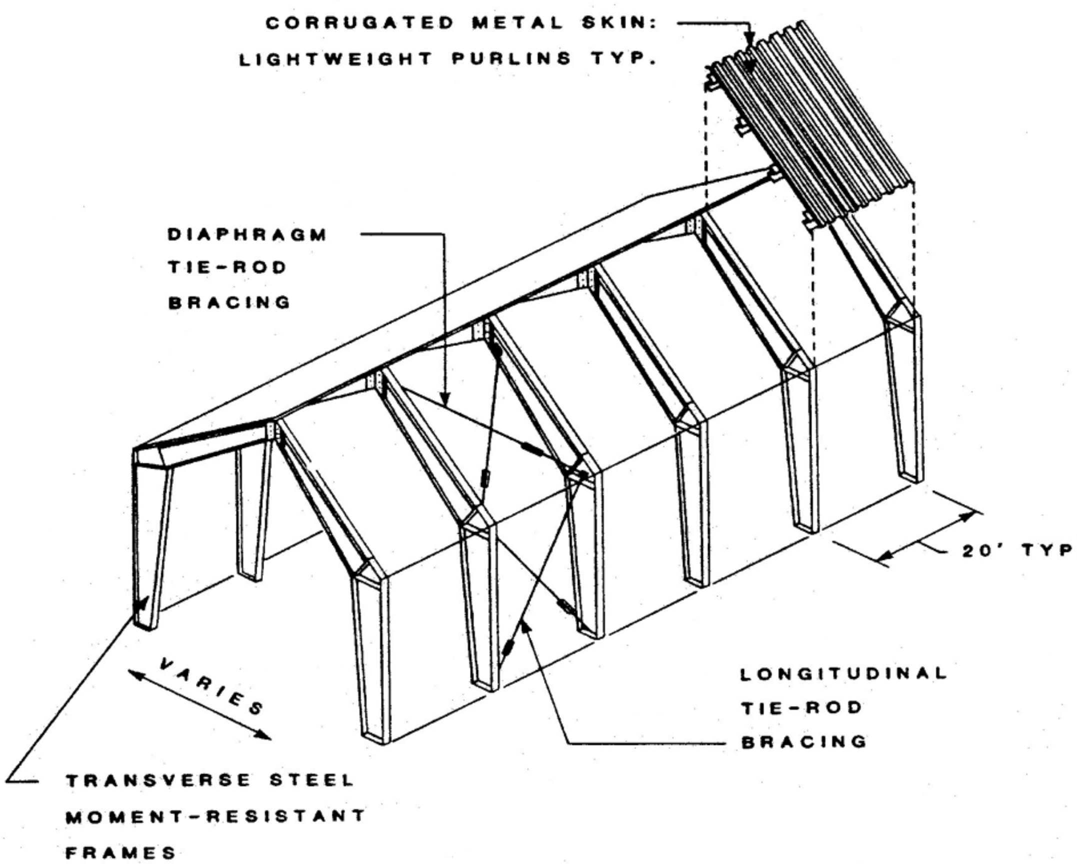


Figure E-17 Drawing of light metal construction.

1. Light metal buildings are typically characterized by industrial corrugated sheet metal or asbestos-reinforced cement siding. The term, "metal building panels" should not be confused with "corrugated sheet metal siding." The former are prefabricated cladding units usually used for large office buildings. Corrugated sheet metal siding is thin sheet material usually fastened to purlins, which in turn span between columns. If this sheet cladding is present, the screener should examine closely the fasteners used. If the heads of sheet metal screws can be seen in horizontal rows, the building is most likely a light metal structure (Figure E-18).

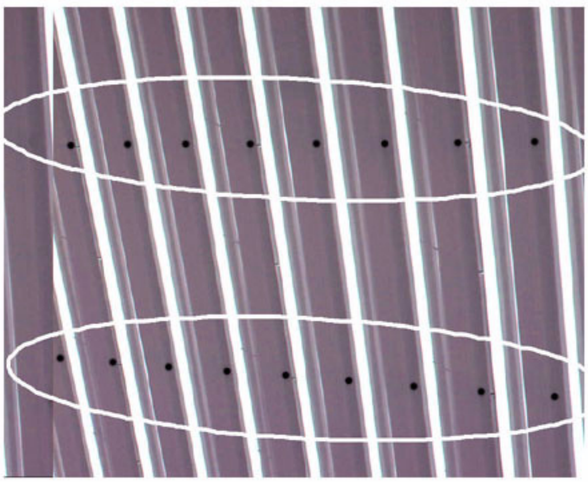

Figure E-18 Connection of metal siding to light metal frame with rows of screws (encircled).

2. Because the typical structural system consists of moment frames in the transverse direction and frames braced with diagonal steel rods in the longitudinal direction, light metal buildings often have low-pitched roofs without parapets or overhangs (Figure E-19). Most of these buildings are prefabricated, so the buildings tend to be rectangular in plan, without many corners.
3. These buildings generally have only a few windows, as it is difficult to detail a window in the sheet metal system.
4. The screener should look for signs of a metal building, and should knock on the siding to see if it sounds hollow. Door openings should be inspected for exposed steel members. If a gap, or light, can be seen where the siding meets the ground, it is certainly light metal or wood frame. For the best indication, an interior inspection will confirm the structural skeleton, because most of these buildings do not have interior finishes.

Figure E-19 Prefabricated metal building (S3, light metal building).

### *E.4.2 Typical Earthquake Damage*

Because these building are low-rise, lightweight, and constructed of steel members, they usually perform relatively well in earthquakes. Collapses do not usually occur. Some typical problems are listed below:

1. Insufficient capacity of tension braces can lead to their elongation or failure, and, in turn, building damage.
2. Inadequate connection to the foundation can allow the building columns to slide.
3. Loss of the cladding can occur.

## E.5 Steel Frame with Concrete Shear Wall (S4)

### *E.5.1 Characteristics*

The construction of this structural type (Figure E-20) is similar to that of the steel moment-resisting frame in that a matrix of steel columns and girders is distributed throughout the structure. The joints, however, are not designed for moment resistance, and the lateral forces are resisted by concrete shear walls.

It is often difficult to differentiate visually between a steel frame with concrete shear walls and one without, because interior shear walls will often be covered by interior finishes and will look like interior nonstructural partitions. For the purposes of an RVS, unless the shear wall is identifiable from the exterior (i.e., a raw concrete finish was part of the architectural aesthetic of the building, and was left exposed), this building cannot be identified accurately. Figure E-21shows a structure with such an exposed shear wall. Figure E-22 is a close-up of shear wall damage.

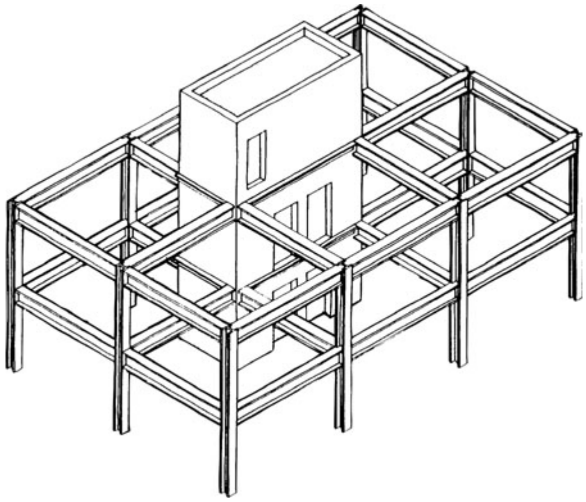

Figure E-20 Drawing of steel frame with interior concrete shear-walls.

Figure E-21 Concrete shear wall on building exterior.

### *E.5.2 Typical Earthquake Damage*

The shear walls can be part of the elevator and service core, or part of the exterior or interior walls. This type of structure performs as well in earthquakes as other steel buildings. Some typical types of damage, other than nonstructural damage and pounding, are:

1. Shear cracking and distress can occur around openings in concrete shear walls.

Figure E-22 Close-up of exterior shear wall damage during a major earthquake.

2. Wall construction joints can be weak planes, resulting in wall shear failure at stresses below expected capacity.
3. Insufficient chord steel lap lengths can lead to wall bending failures.

## E.6 Steel Frame with Unreinforced Masonry Infill (S5)

### *E.6.1 Characteristics*

This construction type (Figures E-23 and E-24) consists of a steel structural frame and walls “infilled” with unreinforced masonry (URM). In older buildings, the floor diaphragms are often wood. Later buildings have reinforced concrete floors. Because of the masonry infill, the structure tends to be stiff. Because the steel frame in an older building is covered by unreinforced masonry for fire protection, it is easy to confuse this type of building with URM bearing-wall structures. Further, because the steel columns are relatively thin, they may be hidden in walls. An apparently solid masonry wall may enclose a series of steel columns and girders. These infill walls are usually two or three wythes thick. Therefore, header bricks will sometimes be present and thus mislead the screener into thinking the building is a URM bearing-wall structure, rather than infill. Often in these structures the infill and veneer masonry is exposed. Otherwise, masonry may be obscured by cladding in buildings, especially those that have undergone renovation.

When a masonry building is encountered, the screener should first attempt to determine if the masonry is reinforced, by checking the date of construction, although this is only a rough guide. A

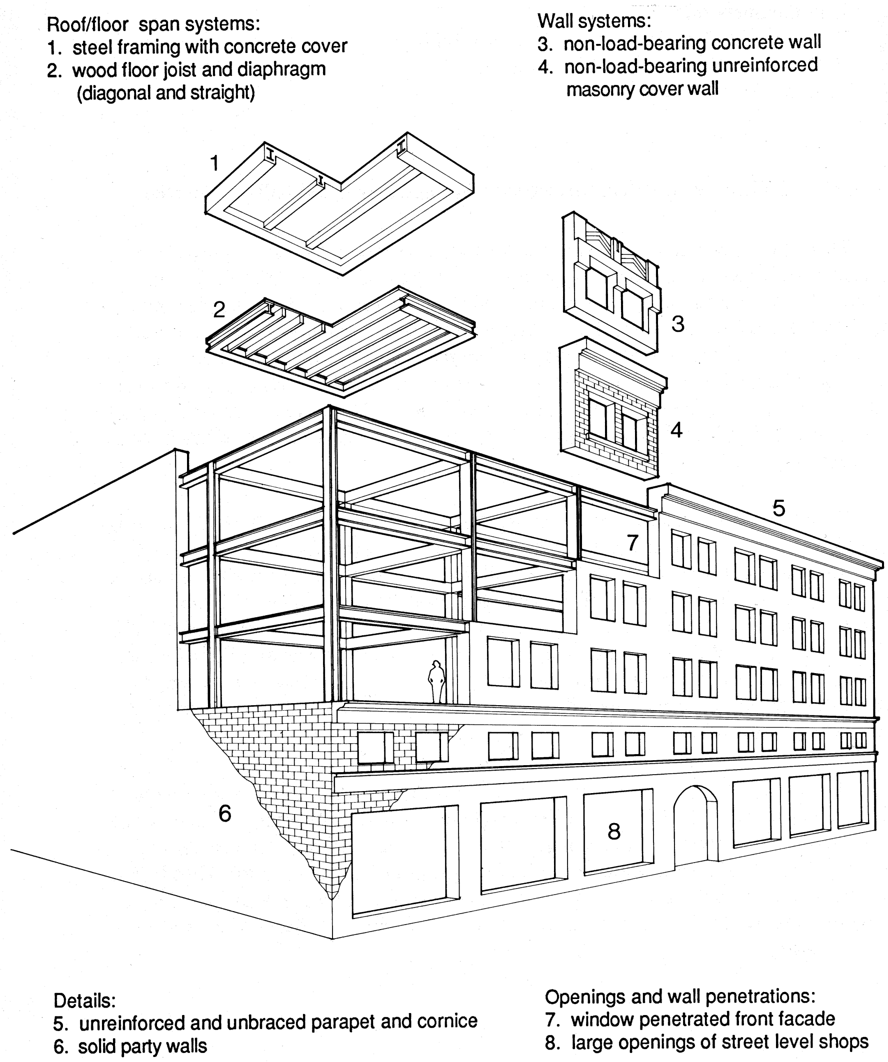


Figure E-23 Drawing of steel frame with URM infill.

clearer indication of a steel frame structure with URM infill is when the building exhibits the characteristics of a frame structure of type S1 or S2. One can assume all frame buildings clad in brick and constructed prior to about 1940 are of this type.

Older frame buildings may be of several types—steel frame encased with URM, steel frame encased with concrete, and concrete frame. Sometimes older buildings have decorative cladding such as terra cotta or stone veneer. Veneers may obscure all evidence of URM. In that case, the structural type cannot be determined. However, if there is evidence that a large amount of concrete is used in the building (for example, a rear wall constructed of concrete), then it is unlikely that the building has URM infill.

When the screener cannot be sure if the building is a frame or has bearing walls, two clues may help—the thickness of the walls and the height. Because infill walls are constructed of two or three wythes of bricks, they should be approximately 9 inches thick (2 wythes). Furthermore, the thickness of the wall will not increase in the lower stories, because the structural frame is carrying the load. For buildings over six stories tall, URM is infill or veneer, because URM bearing-wall structures are seldom this tall and, if so, they will have extremely thick walls in the lower stories.

### *E.6.2 Typical Earthquake Damage*

In major earthquakes, the infill walls may suffer substantial cracking and deterioration from in-plane or out-of-plane deformation, thus reducing the in-plane wall stiffness. This in turn puts additional demand on the frame. Some of the walls may fail while others remain intact, which may result in torsion or soft story problems.

The hazard from falling masonry is significant as these buildings can be taller than 20 stories. As

Figure E-24 Example of steel frame with URM infill walls (S5).

described below, typical damage results from a variety of factors.

1. Infill walls tend to buckle and fall out-of-plane when subjected to strong lateral forces. Because infill walls are non-load-bearing, they tend to be thin (around 9") and cannot rely on the additional shear strength that accompanies vertical compressive loads.
2. Veneer masonry around columns or beams is usually poorly anchored to the structural members and can disengage and fall.
3. Interior infill partitions and other nonstructural elements can be severely damaged and collapse.
4. If stories above the first are infilled, but the first is not (a soft story), the difference in stiffness creates a large demand at the ground floor columns, causing structural damage.
5. When the earthquake forces are sufficiently high, the steel frame itself can fail locally. Connections between members are usually not designed for high lateral loads (except in tall buildings) and this can lead to damage of these connections. Complete collapse has seldom occurred, but cannot be ruled out.

### *E.6.3 Common Rehabilitation Techniques*

Rehabilitation techniques for this structural type have focused on the expected damage. By far the most significant problem, and that which is addressed in most rehabilitation schemes, is failure of the infill wall out of its plane. This failure presents a significant life safety hazard to individuals on the exterior of the building, especially those who manage to exit the building during the earthquake. To remedy this problem, anchorage connections are developed to tie the masonry infill to the floors and roof of the structure.

Another significant problem is the inherent lack of shear strength throughout the building. Some of the rehabilitation techniques employed include the following.

1. Gunite (with pneumatically placed concrete) the interior faces of the masonry wall, creating reinforced concrete shear elements.
2. Rehabilitate the steel frames by providing cross bracing or by fully strengthening the connections to create moment frames. In this latter case, the frames are still not sufficient to resist all the lateral forces, and reliance on the infill walls is necessary to provide adequate strength.

For concrete moment frames the rehabilitation techniques have been to provide ductile detailing. This is usually done by removing the outside cover of concrete (a couple of inches) exposing the reinforcing ties. Additional ties are added with their ends embedded into the core of the column. The exterior concrete is then replaced. This process results in a detail that provides a reasonable amount of ductility but not as much as there would have been had the ductility been provided in the original design.

## E.7 Concrete Moment-Resisting Frame (C1)

### *E.7.1 Characteristics*

Concrete moment-resisting frame construction consists of concrete beams and columns that resist both lateral and vertical loads (see Figure E-25). A fundamental factor in the seismic performance of concrete moment-resisting frames is the presence or absence of ductile detailing. Hence, several construction subtypes fall under this category:

a. non-ductile reinforced-concrete frames with unreinforced infill walls,
b. non-ductile reinforced-concrete frames with reinforced infill walls,
c. non-ductile reinforced-concrete frames, and

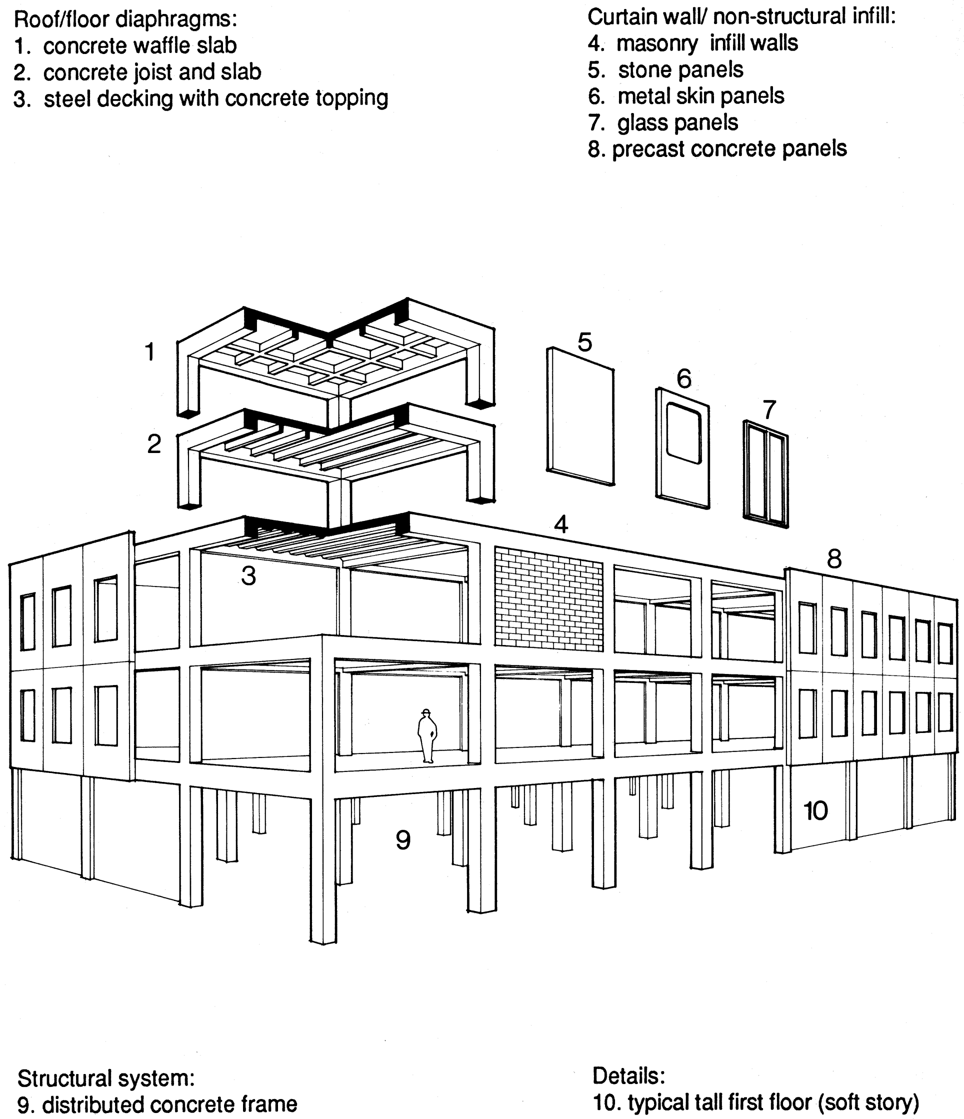


Figure E-25 Drawing of concrete moment-resisting frame building.

d. ductile reinforced-concrete frames.

Ductile detailing refers to the presence of special steel reinforcing within concrete beams and columns. The special reinforcement provides confinement of the concrete, permitting good performance in the members beyond the elastic capacity, primarily in bending. Due to this confinement, disintegration of the concrete is delayed, and the concrete retains its strength for more cycles of loading (i.e., the ductility is increased). See Figure E-26 for a dramatic example of ductility in concrete.

Ductile detailing (Figure E-27) has been practiced in high-seismicity areas since 1967, when ductility requirements were first introduced into the *Uniform Building Code* (the adoption and enforcement of ductility requirements in a given jurisdiction

Figure E-26 Extreme example of ductility in concrete, 1994 Northridge earthquake.

Figure E-27 Example of ductile reinforced concrete column, 1994 Northridge earthquake; horizontal ties would need to be closer for greater demands.

may be later, however). Prior to that time, nonductile or ordinary concrete moment-resisting frames were the norm (and still are, for moderate seismic areas). In high-seismicity areas additional tie reinforcing was required following the 1971 San Fernando earthquake and appeared in the *Uniform Building Code* in 1976.

In many low-seismicity areas of the United States, non-ductile concrete frames of type (a), (b), and (c) continue to be built. This group includes large multistory commercial, institutional, and residential buildings constructed using flat slab frames, waffle slab frames, and the standard beam-and-column frames. These structures generally are more massive than steel-frame buildings, are under-reinforced (i.e., have insufficient reinforcing steel embedded in the concrete) and display low ductility.

This building type is difficult to differentiate from steel moment-resisting frames unless the structural concrete has been left relatively exposed (see Figure E-28). Although a steel frame may be encased in concrete and appear to be a concrete frame, this is seldom the case for modern buildings (post 1940s). For the purpose of the RVS procedures, it can be assumed that all exposed concrete frames are concrete and not steel frames.

Figure E-28 Concrete moment-resisting frame building (C1) with exposed concrete, deep beams, wide columns (and with architectural window framing).

### E.7.2 Typical Earthquake Damage

Under high amplitude cyclic loading, lack of confinement will result in rapid disintegration of nonductile concrete members, with ensuing brittle failure and possible building collapse (see Figure E-29).

Causes and types of damage include:

1. Excessive tie spacing in columns can lead to a lack of concrete confinement and shear failure.
2. Placement of inadequate rebar splices all at the same location in a column can lead to column failure.
3. Insufficient shear strength in columns can lead to shear failure prior to the full development of moment hinge capacity.
4. Insufficient shear tie anchorage can prevent the column from developing its full shear capacity.
5. Lack of continuous beam reinforcement can result in unexpected hinge formation during load reversal.

Figure E-29 Locations of failures at beam-to-column joints in nonductile frames, 1994 Northridge earthquake.

6. Inadequate reinforcing of beam-column joints or the positioning of beam bar splices at columns can lead to failures.
7. The relatively low stiffness of the frame can lead to substantial nonstructural damage.
8. Pounding damage with adjacent buildings can occur.

### *E.7.3 Common Rehabilitation Techniques*

Rehabilitation techniques for reinforced concrete frame buildings depend on the extent to which the frame meets ductility requirements. The costs associated with the upgrading an existing, conventional beam-column framing system to meet the minimum standards for ductility are high and this approach is usually not cost-effective. The most practical and cost-effective solution is to add a system of shear walls or braced frames to provide the required seismic resistance (ATC, 1992).

## E.8 Concrete Shear Wall (C2)

### *E.8.1 Characteristics*

This category consists of buildings with a perimeter concrete bearing-wall structural system or frame structures with shear walls (Figure E-30). The structure, including the usual concrete floor diaphragms, is typically cast in place. Before the 1940s, bearing-wall systems were used in schools, churches, and industrial buildings. Concrete shear-wall buildings constructed since the early 1950s are institutional, commercial, and residential buildings, ranging from one to more than thirty stories. Frame buildings with shear walls tend to be commercial and industrial. A common example of the latter type is a warehouse with interior frames and perimeter concrete walls. Residential buildings of this type are often mid-rise towers. The shear walls in these newer buildings can be located along the perimeter, as interior partitions, or around the service core.

Frame structures with interior shear walls are difficult to identify positively. Where the building is clearly a box-like bearing-wall structure it is probably a shear-wall structure. Concrete shear wall buildings are usually cast in place. The screener should look for signs of cast-in-place concrete. In concrete bearing-wall structures, the wall thickness ranges from 6 to 10 inches and is thin in comparison to that of masonry bearing-wall structures.